THE INFLUENCE OF REINFORCED ELEMENTS ON DEFORMATION BEHAVIOR OF THE ALUMINUM ALLOY

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ABSTRACT.

The hot deformation behaviors of the aluminum alloy PM2014 and metal matrix composite PM2014-20% Al_2O_{3p}, produced via powder metallurgy, have been compared by tension tests in the range of temperatures and strain rates of T=450-525°C and $\varepsilon=10^{-4}$-1.1 s^{-1} respectively. The aluminum alloy and the composite have shown superplastic behavior at these temperatures. The introduction of reinforced elements into the aluminum alloy has led to a decrease of a maximum value of elongation-to-failure (δ) from 450% to 210% and an increase of threshold stress by a factor of 1.5. However, the coefficient of the strain rate sensitivity "m" for hot plastic deformation has changed insignificantly. The optimal strain rate of superplastic deformation for the composite is higher than for the conventional alloy by a factor of 10. The reasons of reinforced elements influence on hot deformation behavior of the aluminum alloy are discussed.

INTRODUCTION.

Recent advances in powder metallurgy technology have resulted in development of new superplastic aluminum alloys and discontinuously reinforced metal matrix composites (**MMC**) on their base. The major advantage of **MMC** is their relatively high elastic modules compared with high-strength aluminum alloys. **MMC** exhibit a unique combination of high specific modulus and strength at room temperature [1,2]. This type of composites is characterized by considerable formability due to that there exists a possibility to manufacture **MMC** parts by using extrusion, forging or rolling technology developed for conventional aluminum alloys. However, this kind of composite shows low hot workability in comparison to the matrix alloys [3]. Reinforced by ceramic elements aluminum alloys usually have a high flow stress and poor strain-to-failure that leads to high extrusion breakout pressures and surface breakup or cracking during forging operation. This retards industrial application of **MMC**.

The use of the effect of high strain rate superplasticity (**HSRS**) provides a unique possibility to overcome this barrier on the way of the commercial application of **MMC** [4-12]. It is known that composites exhibit superplastic behavior at relatively high strain rates ($\varepsilon>10^{-2}$ s^{-1}). The optimal superplastic strain rate in **MMC** is several orders of magnitude larger than that in conventional aluminum alloys. Attempts to explain this phenomenon by comparing hot deformation behaviors of composites and their matrix aluminum alloys were accomplished in [3,4,13,14,18,19]. Evidently, the peculiarities of the investigated materials make the authors [4,10,14] explain the **HSRS** phenomenon as a result of interfacial sliding along the melted interfaces Al/SiC. If the presumption is true, then perspectives of technological application of superplastic deformation of the composites become uncertain, as service properties after this treatment have to drop. From this point of view, the investigation of the influence of reinforced elements on deformation behavior of **MMC** in the absence of interfacial boundaries melting is very important. It allows to develop technique of manufacturing composites by forging operations without their service properties degradation. On the other hand, only a comparison investigation of the composite and their matrix alloy will give an opportunity to understand an unusual phenomenology of hot deformation of **MMC**. The aim of the present paper is to study the effect of reinforced elements on mechanical properties of the aluminum alloy .

MATERIAL AND EXPERIMENTAL PROCEDURES.

The aluminum alloy PM2014 (4.55% Cu, 0.6% Mg, 0.78% Mn, 0.86% Si, 0.06%Fe) and the composite PM2014-20% Al_2O_{3p} were produced via powder metallurgy. The as-received fine structures of the composite matrix and the aluminum alloy are similar. Grain size of both materials constitutes 2.5 μm. Dispersed particles of Θ and Q phases are observed. Their size is 0.1 μm and their volume fraction is approximately 4%. Besides that, small 0.5 μm particles of Al_2O_3 are encountered in aluminum matrix. Their volume fraction is less than 0.5%. The only difference is that subgrain boundaries are observed more often in the aluminum alloy than in the composite structure. Lattice dislocations are distributed uniformly in - matrix of the composite and in body of PM2014 alloy ($\rho=3\pm1.5\cdot10^9$ cm^2).

Tensile specimens, 10 mm in gauge length and 4mm in width, were machined from the extruded bar ∅15mm, with the gauge length parallel to the extruding direction. Tension tests were carried out on a "Instron 1185" universal testing machine at temperatures T=450-525°C and at strain rates $\dot{\varepsilon}=10^{-4}$-1.1 s^{-1}. The flow stress for each test was determined at a true strain of 0.5. The values of the strain rate sensitivity $m=\partial(\lg\sigma)/\partial(\lg\dot{\varepsilon}))$ were measured by the strain rate jump test [15]. The values of the stress exponent $n=\partial(\lg\dot{\varepsilon})/\partial(\lg\sigma)$ in equation (1) were defined from the slope of the lgε-lgσ line.

$$\dot{\varepsilon}= A\,\sigma^n \exp\frac{-Q}{RT} \quad (1)$$

where R = universal gas constant

A = material constant

The threshold stresses were calculated by using a standard graphic approach [16,17].

Differential thermal analysis (DTA) has shown (fig.1) that both materials are stable up to 500°C, and have incipient melting point at 508°C during heating. The small endothermic peak at t=260°C is associated with aging processes in aluminum matrix and suppresses by prior high temperature annealing.

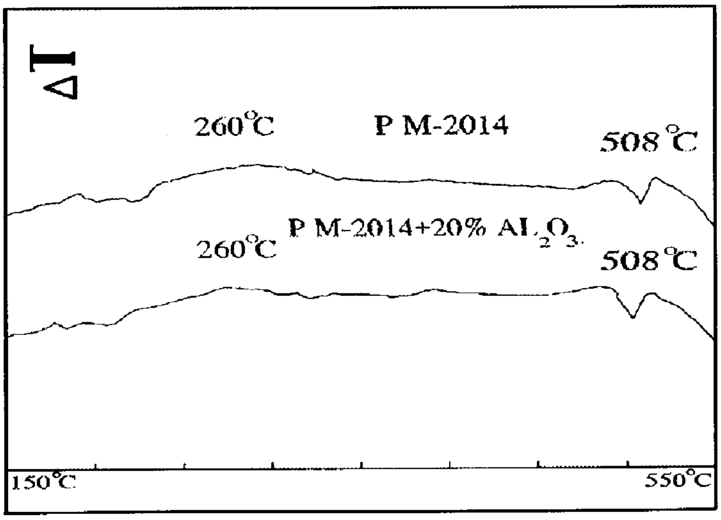

Fig. 1: DTA results illustrating no difference in thermal responce between PM2014-20% Al_2O_{3p} and PM2014 (a heating rate is 10°C/min).

RESULTS.

Stress-strain curves. The true stress-strain curves for the composite and its matrix alloy PM2014 are shown in fig.2. It is seen that shapes of the σ-ε curves for the composite and its matrix are quite different. Let us consider these differences in detail.

True stress-strain curves of the composite for all temperature-strain rate conditions of plastic flow indicate three stages of plastic flow. The sharp strain hardening takes place at the early stage of plastic flow usually at ε=2-10%. The increase of the strain rate at temperature t=500°C leads to a growth of the first stage and a growth of a relative hardening. Thus, at $\dot{\varepsilon}\geq10^{-1}$ s^{-1} the extension of stage 1 reaches ε=20%, and a relative increase of flow stress level constitutes 20-40%. At the same time at $\dot{\varepsilon}\leq10^{-4}$ s^{-1} the first stage is not almost revealed. With decreasing a temperature the influence of the strain rate on specific features of the first stage of plastic flow considerably decreases. The extension of stage I does not exceed ε=5%, and the relative hardening constitutes less than 10%.

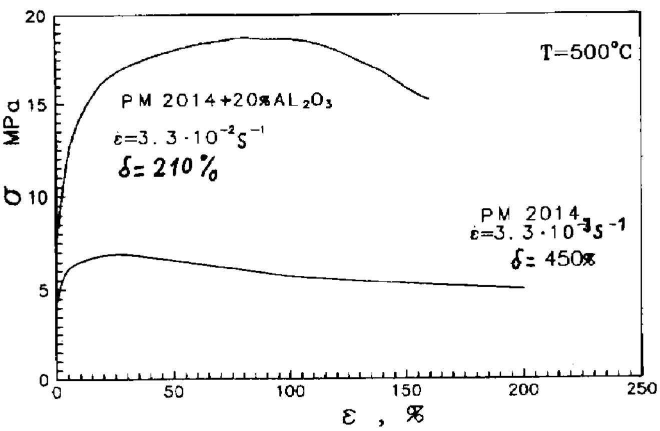

Fig. 2: Stress-strain curves.

At stage 2, the flow stress continues to increase, but slower than at stage I. An increase of the strain rate or a decrease of temperature leads to a decrease of strain, at which the maximum of flow stress attains. Thus, at t=500°C and $\dot{\varepsilon}=3.3\cdot10^{-2}$ s^{-1} the value of a peak strain constitutes about 25%. This is connected with a reduction of the total strain-to-failure. It should be noted that at t=450°C, contrary to high temperatures, a stable stage of plastic flow is observed. Its extension increases with growing the strain rate and constitutes ε=10-70%.

At stage 3, after a stress peak the flow stress slowly decreases. However, this is not observed at all strain rates. At $\dot{\varepsilon}>10^{-1}$ s^{-1} and t=500°C a failure has occurred already at the first stage of plastic flow, and at $\dot{\varepsilon}\leq4\cdot10^{-4}$ s^{-1} and t=450°C at stage 2. The maximum loss of the material strength occurs at t=500°C and $\dot{\varepsilon}=8.3\cdot10^{-2}$ s^{-1}.

The matrix alloy PM2014 demonstrates another type of σ-ε curves. Their shape is typical for dynamic recrystallization [11]. A peak of flow stress is present at all stress-strain curves after which a stable stage of plastic flow reaches. The value and extension of the stress peak insignificantly depend on deformation temperature, and are mainly determined by a strain rate. The stress peak is sharp at strain rate $\dot{\varepsilon}\leq1.6\cdot10^{-4}$ s^{-1} . It has been attained after small strains (ε=1.5-4%) already. Its relative value constitutes 10-30% , and the peak strain constitutes ε=2-5%. An increase in the strain rate makes the situation different. The stress peak shifts to higher strains (ε_{peak}=12-45%). Its extension rises almost by 10 times. The maximum level of flow stress does not change at strains ε=15-30%. The relative value of peak stress constitutes about 50%. The subsequent increase of the strain rate above $\dot{\varepsilon}=8.3\cdot10^{-2}$ s^{-1} again changes the shape of σ-ε curves. They become similar to those described above for the composite.

Strain rate-stress dependence. The best superplastic properties for both materials were observed at t=500°C and only these data will be described in detail. Inspection shows that there is a sigmoidal relationship between the flow stress and the strain rate plotted on a double logarithmic scale (fig.3b) for both materials. Three deformation regions can be distinguished for the composite and their matrix alloy. In all regions the strain rate vs stress dependence is described by power law (1). At the same time values of the stress exponent "n" for each region are individual. It is interesting that "n" values for the composite and the aluminum alloy in the same regions are close. The flow stress vs strain rate dependence is typical for superplastic effect manifestation both in the aluminum alloy [11], and in the MMC [5-9]. In the aluminum alloy at strain rates $\dot{\varepsilon}\leq8\cdot10^{-4}$ s^{-1} and $\dot{\varepsilon}\geq1.6\cdot10^{-2}$ s^{-1} the level of flow stress slowly grows with increasing the strain rate, whereas in region 2 the σ vs ε dependence is very strong. In the composite the situation is analogous, only region 2 is narrower than in the aluminum alloy by a factor of 1.5 and is shifted to the strain rate range that is higher by an order.

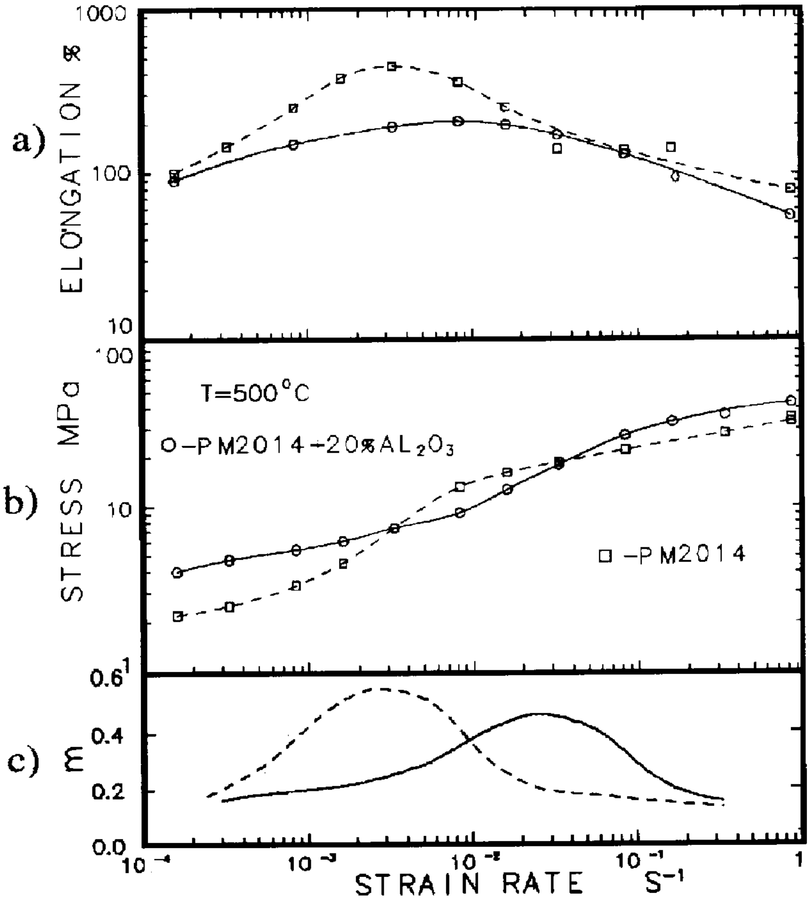

Fig. 3. Elongation (a), flow stress (b) & strain rate sensitivity coefficient "m" (c) as a function of strain rate.

In the interval of the strain rates $\dot{\varepsilon}=3.3\cdot10^{-3}$ –$3.3\cdot10^{-2}$ s^{-1} the level of flow stress in the composite is lower than in its matrix alloy. At other strain rates the flow stresses in the aluminum alloy are lower than in the composite. The similar dependencies were reported in [18,19], where the authors showed that with a growth of the flow stress the creep strain rates of composites became higher than in unreinforced material. In [13] it has been also shown that with decreasing the strain rate the flow stress of a composite becomes lower than in its matrix alloy. One can suppose that in these works the studied strain rate intervals have not been sufficiently wide for revealing a narrow strain rate region where the given dependence is observed. At high or low strain rates the strength of the composite is always larger than that of their matrix alloy. In region 1 the difference between the composite and the aluminum alloy attains 80%, whereas in region 3 it does not exceed 10%.

The coefficient "m" value vs strain rate dependence slightly differs from the stress exponent "n"-$\lg\varepsilon$ dependence (fig.3c). Evidently, this is caused by the difference in the methods of measuring these values [15]. In the composite material the maximum m=0.45 locates in the second region at $\dot{\varepsilon}=3.3\cdot10^{-2}$ s^{-1}. The maximum has a large extension. It is shifted to the regions of higher strain rates as compared to those in the alloy PM2014. In the aluminum alloy the maximum value of m=0.52 is observed at a lower strain rate ($\dot{\varepsilon}=2\cdot10^{-3}$ s^{-1}). The peak at the curve m-lg$\dot{\varepsilon}$ is narrower than in the composite. It should be noted that in region 2 the value of the strain rate sensitivity coefficient is higher for the alloy than for the composite.

Elongation-to-failure. The total elongation-strain rate dependencies for the composite and their matrix alloy are given in fig.3a. It is seen that the total elongation has maximum (δ=210%) for the composite at $\dot{\varepsilon}=1.6\cdot10^{-2}$ s^{-1}, and for the alloy at $\dot{\varepsilon}=2.8\cdot10^{-3}$ s^{-1} (δ=450%). At all strain rates the strain-to-failure of the composite is smaller than for their matrix alloy. Contrary to the m-lg$\dot{\varepsilon}$ dependencies one can say that the strain rates corresponding to the total elongation maximums of both materials are close. At the same time the maximum "δ" of the composite is at the strain rate that is 2.5 times smaller than that of the maximum "m". Such an effect has been early revealed in the composite Si_3N_4/6061 [6]. However, it has not been explained. The increase of test temperature above t=500°C leads to a significant loss in ductility of both materials.

Threshold stresses. In recent works [16,20] it has been shown that the analysis in terms of threshold stress allows to explain the peculiarities of high temperature deformation behavior of composite materials. In order to examine the possibility of existing the threshold stress (σ_{th}) during superplastic deformation **(SPD)**, the experimental data obtained for both materials at temperature t=500°C for regions 1 and 2 were replotted as $\dot{\varepsilon}^{1/2}$ against σ on a double linear scale (fig.4) [17]. The datum points for both materials exactly fit with single straight lines whose extrapolation to zero strain rate gave the values of σ_{th} . Threshold stresses were found to be 2.85 and 1.8 for the composite and their matrix alloy, respectively. It is seen that incorporation of reinforced elements into the aluminum alloy leads to a growth of the threshold stress by a factor of 1.5. Besides, the analysis performed in terms of threshold stress shows that true values of the stress exponent n^*=2 in both materials are similar.

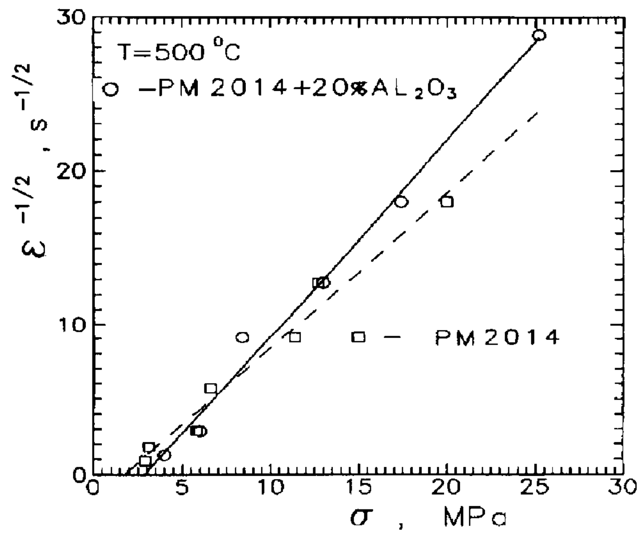

Fig. 4. A plot of $\dot{\varepsilon}^{1/2}$ against σ.

DISCUSSION.

As seen from the presented results, the phenomenological manifestations of **SPD** are similar in the composite and their matrix alloy. The main features of **SPD** [11,22] are as follows:

(i) a sigmoidal relationship between σ and ε , dividing the deformation behavior into three regions;

(ii) high elongation to failure in region 2 and decreases in δ both at low strain rates in region 1 and high strain rates in region 3;

(iii) the coefficient of strain rate sensitivity m>0.3 in region 2 and decreases in "m" both at low strain rates in region 1 and high strain rates in region 3,

(iv) the existence of the optimal temperature of **SPD**. The rise of deformation temperature above the incipient melting point leads to a dramatic decrease in resource of plasticity. It's observed both in the composite and in the aluminum alloy.

Consequently, one can suppose [11], that micromechanisms of deformation acting in the composite PM2014-20% Al_2O_{3p} and in their matrix alloy are the same and are typical for **SPD** of conventional materials. The reason of this phenomenon is the fact that hot deformation behavior of composite materials is determined by matrix.[21]. The main mechanism of deformation in both materials is grain boundary sliding **(GBS)** along the grain boundaries Al/Al [11,22]. The incorporation of reinforced particles, does not change the physical processes of **SPD**, and leads to changes of **GBS** character [21] in the composite and their matrix alloy. This results in different deformation behavior of the materials.

The origin of the observed threshold stresses is connected with the presence of disperse particles Al_2O_3 in the composite matrix and in the body of the alluminum alloy [20]. Evidently, the localization of deformation in the composite matrix caused by reinforced particles [21] is the reason of higher threshold stress in this material.

Thus, it has been shown, that the phenomenology of superplastic deformation of PM2014-20% Al_2O_{3p} composite and their matrix alloy is the same. The differences in the deformation behavior of both materials have a quantitative character and caused by the reinforced elements influence on deformation processes in aluminum matrix.

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